

DRAG REDUCTION IN NUTRIENT SALINE SOLUTION: EFFECT OF CONCENTRATION AND DEGRADATION

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Abstract. Drag reduction by high molecular weight polymers has been studied over the past decades and presents several applications in many industrial processes. Soluble drag reducing polymers have also been shown to produce beneficial effects on blood circulation and may represent a way to treat cardiovascular disorders, like atherosclerosis and hypertension. However, the efficiency of these polymers as friction factor reducers is not constant due to degradation caused by the turbulent flow. In the present work, we investigate the effects of concentration and degradation of a soluble polymer in the drag reduction capacity of a nutrient Krebs-HEPES saline solution. Polyacrylamide (PAM) is tested in a cylindrical double gap rheometer device for the concentrations of 10, 50 and 100ppm. Viscosity and flow curves were obtained for all concentrations, in order to understand the rheological characterization of the fluid, and constant shear rate tests were performed to analyze the loss of efficiency along the time of the experiments. All the tests were conducted using both distilled water (reference solution) and Krebs-HEPES (nutrient saline solution) as solvent. Our findings suggest that the nutrient saline solution composition doesn't make the polymer to react differently, causing no change in drag reduction behavior. The results may contribute to better understand the interaction of polymers chains with a different solvent, which has physiological applications.

Keywords: Bioengineering, rheology, drag reduction, polymer, nutrient saline solution

1. INTRODUCTION

The friction factor reduction by addition of drag reducing polymers has been studied since Toms (1948) had reported this phenomenon. The author showed that the addition of small concentrations of polymers of long chains and high molecular weight reduce significantly the resistance to turbulent flow in tubes, what implies an increase in flow rate at constant pressure drop or a decrease in pressure drop at constant flow rate. Toms' effect has been intensively studied and has shown great success in many industrial processes like pipeline transportation (Burger and Chorn, 1980, Nijs, 1995), operation in oil wells, irrigation process (Singh et al., 1985) and firefighting system (Fabula, 1971, Figueredo and Sabadini, 2013). It was also found that the reduction in hydrodynamic resistance is efficient in non-turbulent flow systems, such as pulsating flow (Driels and Ayyash, 1976). This find was extremely important to make the phenomenon useful in biomedical applications, enabling the use in reducing blood pressure and preventing cardiovascular disorders, such as arteriosclerosis and hemolysis. The phenomenon itself is complex due to the interaction between the polymer long chains and the turbulence, in vascular flow applications, it became much more complex due to a non-permanent and pulsating flow, irregular velocity profile and possible interactions with tissue cells. One of the first studies in drag reduction, DR, in vascular flow was made by Mostardi et al. (1976), which has observed a decrease in flow perturbation in aorta artery of dogs when Separan AP-30 (a polymer similar to polyacrylamide) was injected in the blood system. Greene et al. (1970) has simulated a pulsating flow in a glass tube using a solution of 40ppm of polyacrylamide in calf blood and has obtained 30 percent of drag reduction. Experiments about preventing lethality in hemorrhagic shock was presented by Kameneva et al. (2004). Bessa et al. (2011) reproduced a pulsating flow in the tail arterial bed of rats using polyethylene glycol as drag reducing agent. Kameneva (2012) made a good review about in vitro and in vivo studies on drag reduction in blood

circulation. The biggest limitation of the use of drag reduction in industrial systems or biomedical treatments is the irreversible mechanic degradation of the polymer chains caused by the shear forces imposed by the turbulent flow. Researches have demonstrated that polymer degradation is dependent on concentration, molecular weight, Reynolds number, temperature and solvent properties (Soares et al., 2015 and Andrade et al., 2015). Regarding the solvent for DR polymers, different nutrient saline solutions are used as bathing medium for organs, tissues and cells “ex vivo”, basically Krebs or Tyrode solutions, buffered with bicarbonate-carbon dioxide or organic buffers like HEPES, PIPES or TRIS. In any case, the purpose of these solutions is to preserve the isolated organ under a more physiologic condition, i.e. maintaining the osmolality, ionic strength, nutrition, oxygenation and pH at appropriate levels. However, these saline solvents can interact in a different way with the polymer, causing a distinct drag reduction behavior from the one observed in pure water. Thus, the main goal of the present work is to investigate the drag reduction in a nutrient Krebs-HEPES saline solution as solvent in order to analyze the influence of its components in the DR mechanisms. Although the experiments were conducted in a rotational apparatus and not in a pulsating flow, it can bring good qualitative results to understand the mechanism.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

In this work the tests were carried out using a commercial rheometer, model HAAKE MARS II, manufactured by Thermo Scientific, Germany. We obtained our results by using a double gap cylindrical geometry, the experimental procedure and geometry used are quite similar to that used by Pereira and Soares (2012) and Pereira et al. (2013). The sample was located between the two rigidly interconnected coaxial and stationary surfaces, which have an axial symmetry. The rotor is a thin-walled coaxial tube located between these two fixed cylindrical surfaces which can rotate over the sample holder’s axis of symmetry at a given angular velocity. This geometry was used due to its large contact area, which provides measurements in small Reynolds numbers with good accuracy. The sample volume is 6.3 ml. The dimensions of test section shown in Fig.1 are: $R_1=17.75\text{mm}$, $R_2=18.00\text{mm}$, $R_3=21.40\text{mm}$, $R_4=21.70\text{mm}$ and $L=55.00\text{mm}$.

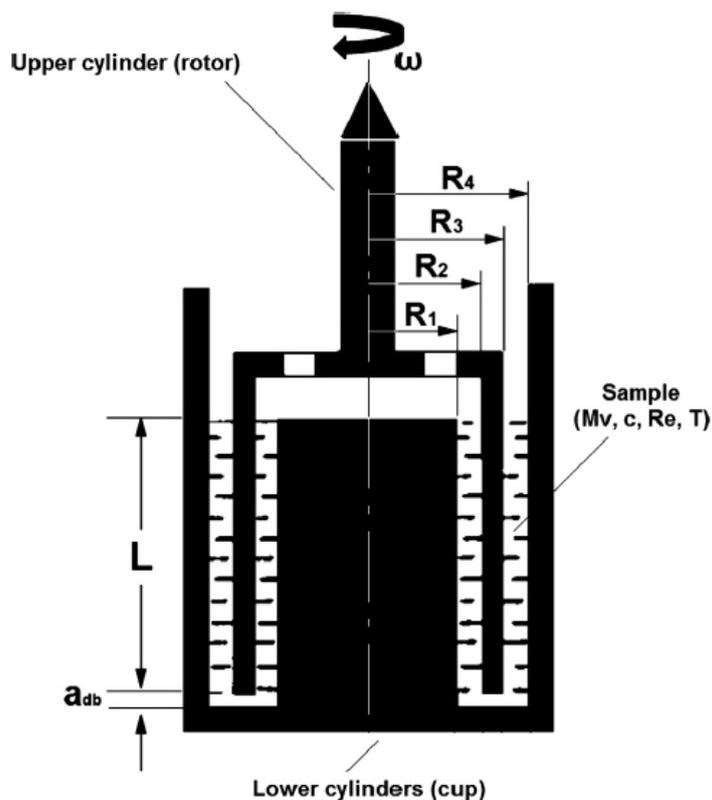


Figure 1 - Schematic illustration of the axial symmetric double gap geometry.

For a given angular velocity, ω , the mean shear rate, $\dot{\gamma}$, is determined as a function of the upper cylinder rotational speed and the nominal shear stress as a function of the applied torque. The rotor reaches its final angular velocity in less than 3 seconds. Only after such period of time, we calculate the Fanning friction factor, f , using Eq. (1) which is based on the shear stress, τ , the solution’s density, ρ , and characteristic velocity, $\omega \bar{R}$, where \bar{R} is the mean radius given by $\bar{R} = (R_2 + R_3)/2$.

$$f = \frac{2\tau}{\rho u^2} = \frac{2\tau}{\rho(\omega R)^2} \quad (1)$$

The Reynolds number is defined by Eq. (2):

$$Re = \frac{\rho \bar{h} u}{\eta} = \frac{\rho(\bar{h})(\omega R)}{\eta} \quad (2)$$

Where η is the solution's viscosity and $\bar{h} = ((R2 - R1) + (R4 - R3))/2$ is the average gap. Finally, the drag reduction is calculated by Eq. (3) as defined by Lumley (1969):

$$DR = 1 - \frac{f}{f_0} \quad (3)$$

Where f and f_0 are, respectively, the friction factor of the solution and solvent.

We have tested solutions of polyacrylamide, PAM, molecular weight $M_v = 5.0 \times 10^6$ g/mol. Our chemical supplies were provided by Sigma–Aldrich. The polymer used was the same tested by Pereira and Soares (2012), which have obtained the molecular weight by calculating the intrinsic viscosity using the Huggins equation and have find values very close to the ones quoted by Sigma–Aldrich. All the tests were conducted using both distilled water (reference solution) and Krebs-HEPES (nutrient saline solution) as solvent in three different concentrations 10, 50 and 100 ppm of PAM, which implies diluted solutions. To prepare the solutions, we first have made concentrated solutions with 1000, 5000 and 10000 ppm, respectively, using distilled water as solvent. After 7 days, the concentrated solutions were diluted into this respective final concentration in distilled water and Krebs-HEPES and these solutions rested for 1 day to complete diffusion before being tested. Before all the tests, the sample rested into the test geometry over 1500 seconds to achieve the desired temperature, 37°C, which was chose for being similar to the human body temperature. Krebs-HEPES' composition in shown in Tab. 1.

Table 1 - Krebs-HEPES composition.

| Compound | Parts per Million |
|---------------------------------------|-------------------|
| NaCl | 5704 |
| KCl | 345 |
| MgSO ₄ . 7H ₂ O | 292 |
| KH ₂ PO ₄ | 134 |
| CaCl ₂ . 2H ₂ O | 275 |
| NaHCO ₃ | 2069 |
| HEPES | 4697 |
| Glucose | 1970 |

Viscosity and flow curves were obtained for all concentrations in order to understand the rheological characterization of the fluid. These tests were performed gradually increasing the rotational speed from 0 to 3000 rpm, which is the maximum speed of our equipment, the Fanning friction factor was displayed as a function of Reynolds number, and it was measured at 600 points over 600 seconds, sufficient time to develop the turbulent microstructures.

Constant shear rate tests were performed to analyze the loss of efficiency along the time of the experiments. The tests with a constant rotation speed were used to display drag reduction as function of time and it extended over 3600 seconds. 7200 points in logarithmic scale were measured.

3. RESULTS AND DISCUSSION

In Figure 2 we show the Fanning friction factor in Prandtl-von Kármán coordinates for three different concentrations of Polyacrylamide, PAM, diluted in distilled water, DW, and Krebs-HEPES nutrient saline solution, Krebs. The rotation speed was gradually increased from 0 to 3000 rpm over 600 seconds. As widely reported by a number of researchers, the friction factor falls with increasing concentration. It is clear that the curves at different concentrations become far from each other with increasing Reynolds number, which implies that the slopes of the curves are an increasing function of concentration, as reported by Pereira et al., 2013.

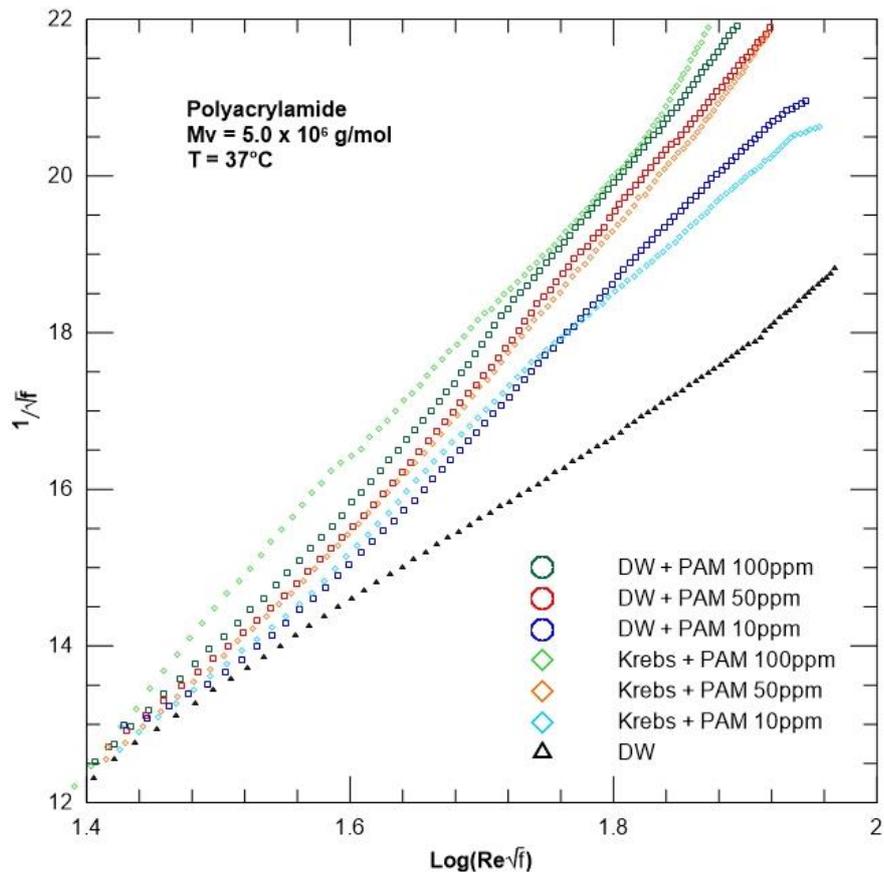


Figure 2 - Fanning friction factor, f , in Prandtl-von Kármán coordinates, as function of Reynolds number, Re .

In Figure 3 shows the effect of the concentration of PAM on drag reduction with time to take in account the loss of efficiency of the polymer as drag reducer. The tests were carried out in the fix Reynolds number of 1360, where the rotation speed was kept constant over the 3600 seconds of measurement. As expected, the drag reduction efficiency increase by increasing the solution concentration. A maximum level of drag reduction is sustained during a period, named resistance time (Pereira et al., 2013), after that time the molecular scission became more pronounced and the efficiency of the polymer decreased until it reaches its asymptotic value, when the degradation of the polymer chains stops and molecular weight achieves a steady state. In our tests the asymptotic value is not so clear, mainly for the concentration of 10ppm, because after 3600 seconds the evaporation of the sample became very pronounced, making the measurements not so clear and accurate.

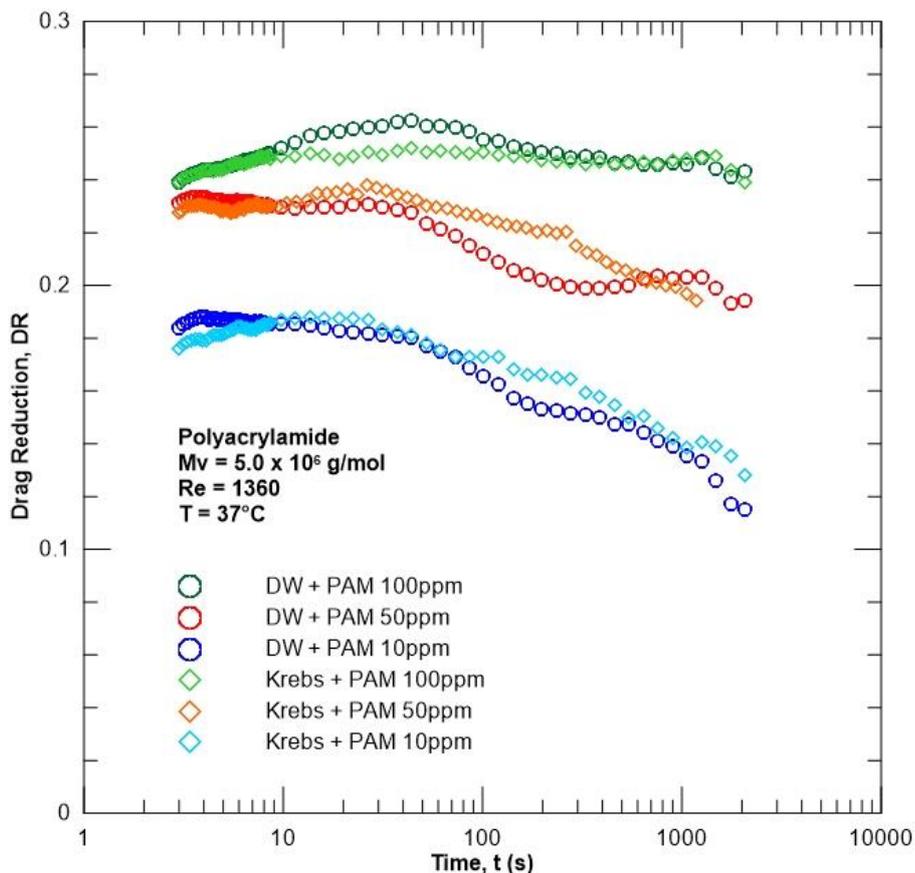


Figure 3 - Effect of concentration on DR as function of time.

We can see in Fig. 3 that the drag reduction decay over the time and this loss of efficiency is more pronounced for the lower concentrations of polymer, for solutions of 100 ppm. The maximum level of efficiency is maintained around 24% of DR over all test time, while solutions of 50 ppm and 10 ppm had DR around 23 and 18%, respectively in the beginning of the test and its value decrease to 20 and 12% in the end, what suggests that high concentrated solutions are more resistant to the degradation imposed by the flow.

Here our main interest is to highlight the differences between solutions in distilled water and the nutrient saline solution. It seems that the composition of the nutrient solution does not affect the phenomenon of drag reduction in PAM solutions. Several saline nutrient solutions are traditionally used in studies with post-hemorrhagic resuscitation (Yamakawa et al 1990; Jacob et al 2006), biomechanical studies concerning the relationship between flow-pressure-resistance in vascular systems (Bergh et al 2005; Ogasa et al 2001; Porret et al 1998), and in vitro studies on organ transplantation and recirculation regimen (Weinbroum et al 2001; Harris et al 2015). Moreover, in vitro studies on the effects of drug/toxins (Silva et al 2016; dos Rossoni et al 2003), heavy metals (Massaroni et al 1992; Fioresi et al 2013) or vascular diseases (dos Santos et al 2003; dos Santos et al 2006; Tucci et al 2007) in different isolated and perfused organs also are obligatorily conducted under perfusion with such buffered saline solutions to maintain oxygenation and nutrition of the tissue. As shown in Fig. 2 and Fig. 3, the results obtained for both solvents presents quite the same behavior. Similar results were obtained by Andrade et al. (2015) that have tested polymers in synthetic seawater, also a saline solvent, and found no significant change in drag reduction in PAM solutions.

4. CONCLUDING REMARKS

We present an experimental approach developed to analyze the differences in drag reduction behavior when using a saline nutrient solution or distilled water as solvent to polyacrylamide solutions. We evaluated the effect of different concentrations of PAM in flow curves and constant shear rate tests and the results shows that the saline characteristic of the nutrient solution seems to cause no effect in DR behavior for PAM solutions.

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